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Micromagnetic simulation of thermally assisted magnetization reversal in magnetic nanodots with perpendicular anisotropy

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Abstract

Temporal evolution of magnetization in a field cooling process from magnetic ordering temperature has been numerically investigated for magnetic nanodots with perpendicular anisotropy by solving the stochastic Landau–Lifshitz–Gilbert equation. The magnetic field required to align the magnetization, i.e. the switching field for thermally assisted writing of magnetic dot, depends on not only the intrinsic anisotropy field but also the magnetization reversal mechanism. To minimize the switching field with ensuring a practical thermal stability of the dot for nonvolatile memory applications, the lateral dimension of the dot should be smaller than its critical size for single domain configuration to avoid a formation of flux closure configuration inside the dot.

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Keywords: Numerical simulation; Nanodot magnetic; Perpendicular anisotropy; Thermally assisted; Magnetization reversal

In order to realize magnetic random access memories (MRAMs) with an areal density of Gbits/cm^2 order, the magnetic anisotropy of the storage layer should be large enough to ensure practical thermal stability for the nonvolatile memory application. Ferromagnets with a large perpendicular magnetic anisotropy such as CoPt, FePt are considered to be promising candidates for storage layer materials in MRAMs. The normalized magnetization decay for logarithmic time, $\Delta M/(M_r/\log t)$ for CoPt nanodots (80 nm in diameter) measured by Aoyama et al. [1] is 0.11%/decade at 350 K and 0.5 kOe reverse field, which is less than one-fifth that of the conventional longitudinal media. However, the magnitude of magnetic field required for switching is still in kOe order, which is too large to generate by pulsed current flowing through conductor lines in MRAMs. Thermally assisted magnetization reversal, where the switching field is temporally reduced by heating the selected memory cell in the writing process, is considered to be a key technology to circumvent this problem.

In this article, the temporal evolution of magnetization ordering along a bias field direction during a field cooling process has been numerically investigated. All calculations are started from the Curie temperature, T_c, so that the randomly distributed magnetization configuration is used for the initial state. The thermal fluctuation effect in the magnetization process is approximately considered by involving the randomly directed effective field in the Landau–Lifshitz–Gilbert (LLG) equation. To evaluate the switching probability at given bias field amplitude, each calculation was performed for 50 different series of random field. The strength of the random field due to thermal fluctuation effect is calculated using the fluctuation dissipation theorem [2]. In our model, an amorphous ferrimagnetic material is considered as a composition of magnetic nanodots, so that the second-power temperature dependence with the thermally reduced magnetization was assumed for both the exchange stiffness constant, A, and the perpendicular crystalline anisotropy, $K_\perp$ [3]. The amplitude of A at 300 K is fixed as 1.0×10^{-7} erg/cm. The dimension of the dot is $50 \times 50 \times 20\,\mathrm{nm}^3$, and its Curie temperature, T_c, is assumed as 373 K. In the field cooling process from the T_c, the temperature is linearly decreased for 2.5 ns. The Gilbert damping constant is 0.3 and the

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integration time step is 0.25 ps. The energy barrier height, ΔE, for the perpendicularly magnetized dot is generally given by $(K_\perp - 2\pi M_s^2)V$, where M_s is the saturation magnetization and V the volume of the dot. It is noted that the M_s and $K_\perp$ values of the dot are selected to satisfy the practical thermal stability, i.e. $\Delta E = 60k_BT$, at 300 K.

Figs. 1(a) and (b) show the temporal evolution of magnetization in the field cooling process calculated for (a) $K_\perp = 7.0\times10^4\,\mathrm{erg/cm^3}$, $4\pi M_s = 0.71\,\mathrm{kG}$, and (b) $K_\perp = 5.5\times10^5\,\mathrm{erg/cm^3}$, $4\pi M_s = 3.5\,\mathrm{kG}$, respectively. When the Bloch-type domain wall is assumed, it is expected that the domain wall is shrunk with increasing not only the $K_\perp$ but also the M_s. In the former case, single domain configuration with positive or negative magnetization is dominated after zero field cooling. The domain wall width, δ_w, formed in the infinite film (20 nm in thickness) numerically evaluated using $K_\perp = 7.0\times10^4\,\mathrm{erg/cm^3}$, $4\pi M_s = 0.71\,\mathrm{kG}$, and $A = 1\times10^{-7}\,\mathrm{erg/cm}$ is 37 nm, which is almost the same order with the lateral dimension of the dot. On the contrary, in the latter case, the numerically evaluated δ_w ($=13$ nm) is much smaller than the dot size. Consequently, the magnetic nanodot tends to relax into a multidomain configuration. In this case, the thermally assisted magnetization reversal is realized via inverse domain annihilation followed by a domain wall propagation.

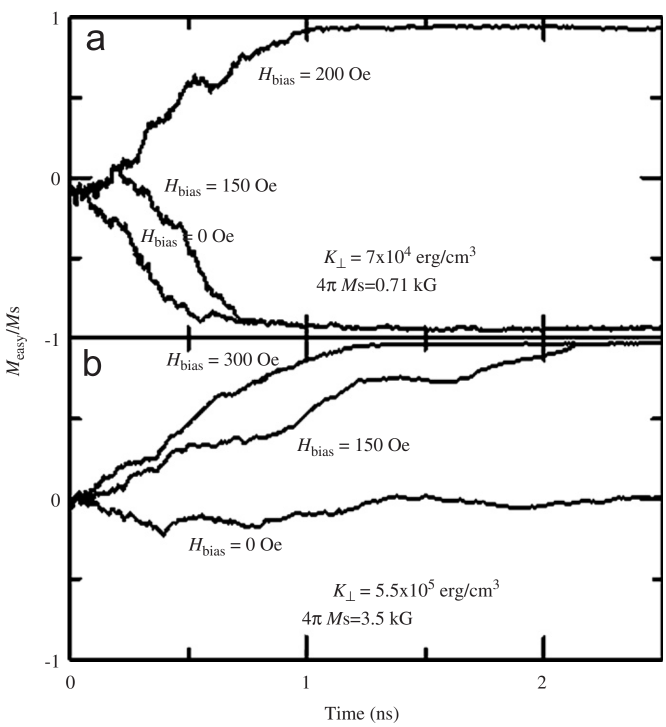

Fig. 1. Temporal variation of reduced magnetization M_{easy}/M_s during a field cooling process calculated for the particle with (a) $K_\perp = 7.0\times10^4\,\mathrm{erg/cm^3}$, $4\pi M_s = 0.71\,\mathrm{kG}$, and (b) $K_\perp = 5.5\times10^5\,\mathrm{erg/cm^3}$, $4\pi M_s = 3.5\,\mathrm{kG}$.

Fig. 2(a) shows the switching probability as a function of the bias field amplitude calculated for various $K_\perp$ ranged from 7.0×10^4 to $5.5\times10^5\,\mathrm{erg/cm^3}$. When the reduced magnetization component parallel to the bias field direction, M_{easy}/M_s, exceeds 0.85, it is found that the inversed domain is completely annihilated. To evaluate the switching probability, the occurrence of the switching event is, therefore, judged if the M_{easy}/M_s exceeds 0.85 or not. As shown in Fig. 2(a), the switching probability gradually increases with the H_{bias} and reaches to 1 at a threshold field which corresponds to the switching field, H_{swt}, required for thermally assisted writing. For zero bias fields, the switching probability differs from one case to the other due to the different domain configurations as expected in the above paragraph. In case the single domain configuration magnetization is dominated, the switching probability tends closely to 0.5 values and vice versa. When the $K_\perp$ is smaller than $1.5\times10^5\,\mathrm{erg/cm^3}$, the probability for the

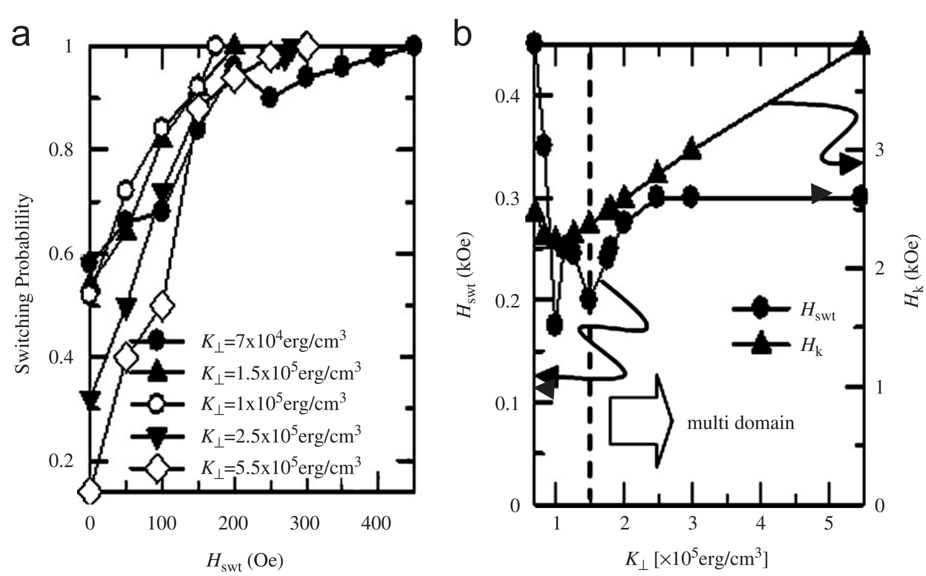

Fig. 2. (a) Switching probability as a function of the bias field amplitude calculated for various $K_\perp$. (b) Switching field H_{swt} and intrinsic anisotropy field H_k ($=2K_\perp/M_s$) as a function of $K_\perp$.

magnetization to relax into positive direction takes the medium value around 0.5 when the zero field is applied. This suggests that the single domain configuration is preferably realized. On the contrary, when the $K_{\perp}$ becomes larger than $1.5 \times 105\,\mathrm{erg/cm^3}$, a multidomain configuration which has the $M_{\mathrm{easy}}/M_{\mathrm{s}}$ values smaller than 0.85 is dominantly formed. Consequently, the probability for the remarkably suppressed from 0.5 which is realized for single domain dominated case. Fig. 2(b) shows the H_{swt} and the intrinsic anisotropy field, H_k $(=2K_{\perp}/M_{\mathrm{s}})$, as a function of $K_{\perp}$. In these calculations, the M_{s} value correlatively changed with the $K_{\perp}$ so as to satisfy $\Delta E=(K_{\perp}-2\pi M_{\mathrm{s}}^2)V=60k_{\mathrm{B}}T$ at 300 K. The H_k value, therefore, takes a minimum at $K_{\perp}=1.0\times 105\,\mathrm{erg/cm^3}$. The H_{swt} almost seems to increase with the H_k. As shown in Fig. 2(b), the H_{swt} is increased and gradually saturated to 300 Oe as the $K_{\perp}$ becomes larger than $1.5\times 10^5\,\mathrm{erg/cm^3}$, where the multidomain configuration is dominated. In the case of nanodots with perpendicular anisotropy, the formation of inversed domain produces a closure flux configuration, which leads to the increase of H_{swt}. The minimum H_{swt} of 175 Oe is obtained for $K_{\perp}=1.0\times 10^5\,\mathrm{erg/cm^3}$ and $4\pi M_{\mathrm{s}}=1.1\,\mathrm{kG}$. Unfortunately, we cannot find the condition to realize $H_{\mathrm{swt}}<100$ Oe, which is generally required for the practical MRAM application. For a further decrease of H_{swt}, an additional mechanism to generate a bias field such as interlayer exchange field in a magnetic bilayer system [4] is required.

In summary, we have numerically investigated magnetization reversal in the field cooling process for magnetic nanodots with perpendicular magnetic anisotropy. The formation of multidomain configuration increases the switching field because the flux closure configuration is preferred for the perpendicular medium. To minimize the switching field, the perpendicular anisotropy and the saturation magnetization of the dot should be chosen so as not only to reduce the intrinsic anisotropy field but also to dominate the single domain configuration.

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References

[1] T. Aoyama, K. Uchiyama, T. Kagotani, K. Hattori, Y. Wada, S. Okawa, H. Hatate, H. Nishio, I. Sato, IEEE Trans. Magn. 37 (2001) 1646.
[2] W.F. Brown Jr., Phys. Rev. 130 (1963) 1677.
[3] M. Mansuripur, G.A.N. Connel, J. Appl. Phys. 55 (1984) 3049.
[4] Y. Nozaki, Y. Isowaki, A. Hashimoto, B. Purnama, K. Matsuyama, J. Magn. Soc. Jpn. 30 (6-2) (2006) 574.